Nano-structured magnetic materials: novel physics and emerging technologies

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Introduction to recording, scaling and nano ‘issues’

Opportunities for nanosciences

- Novel materials and architectures
- Advance characterization

HITACHI

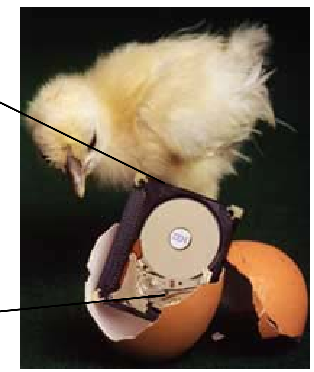
Inspire the Next

Product scaling

Smaller & faster

100 Gbyte
mobile drive

8 Gbyte

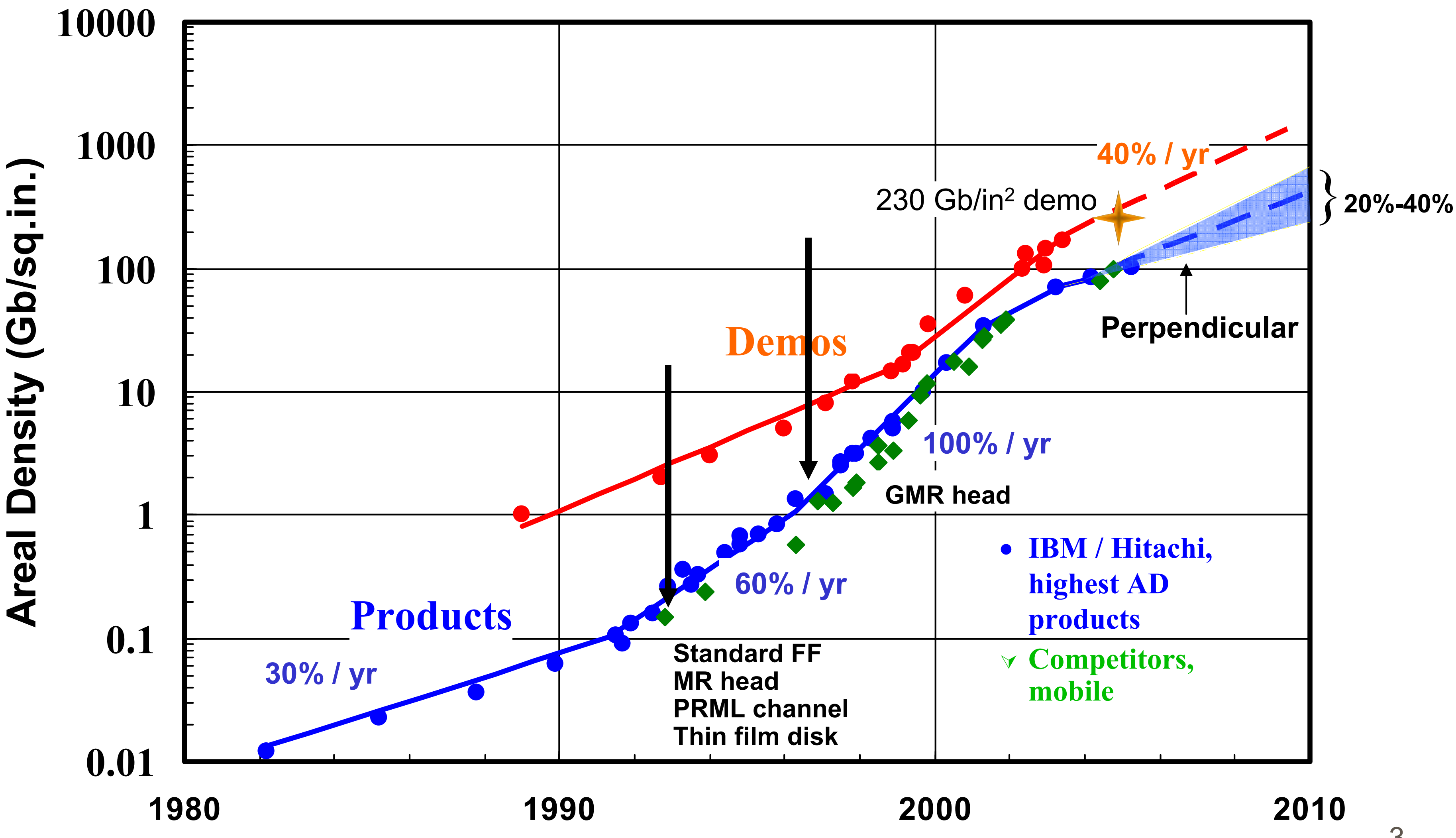


2 kbits/in^2
70 kbits/s
50x 24 in dia disks
$10,000/Mbyte

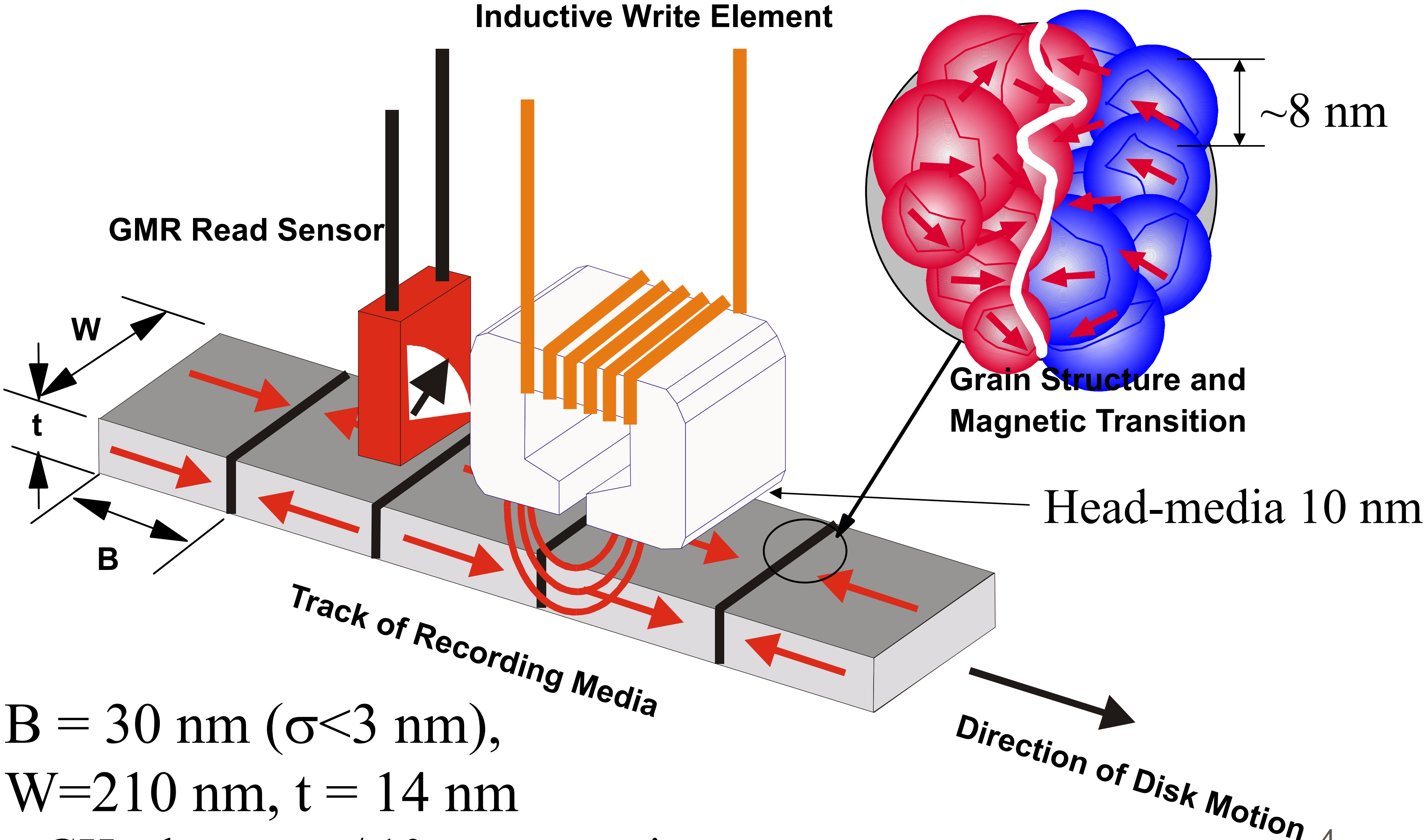
100 Gbits/in^2
630 Mb/s
2 x 2.5”glass disks
<$0.01/Mbyte

Microdrive
78 Gbits/in^2
1 x 1” dia disk

Areal density trends



Magnetic recording components



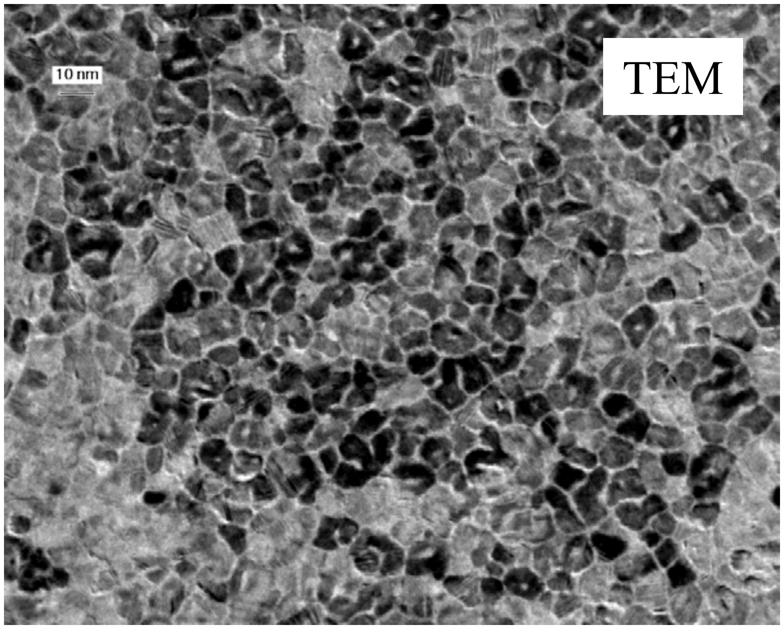
B = 30 nm (σ<3 nm),

W=210 nm, t = 14 nm

~ GHz data rates / 10 year retention

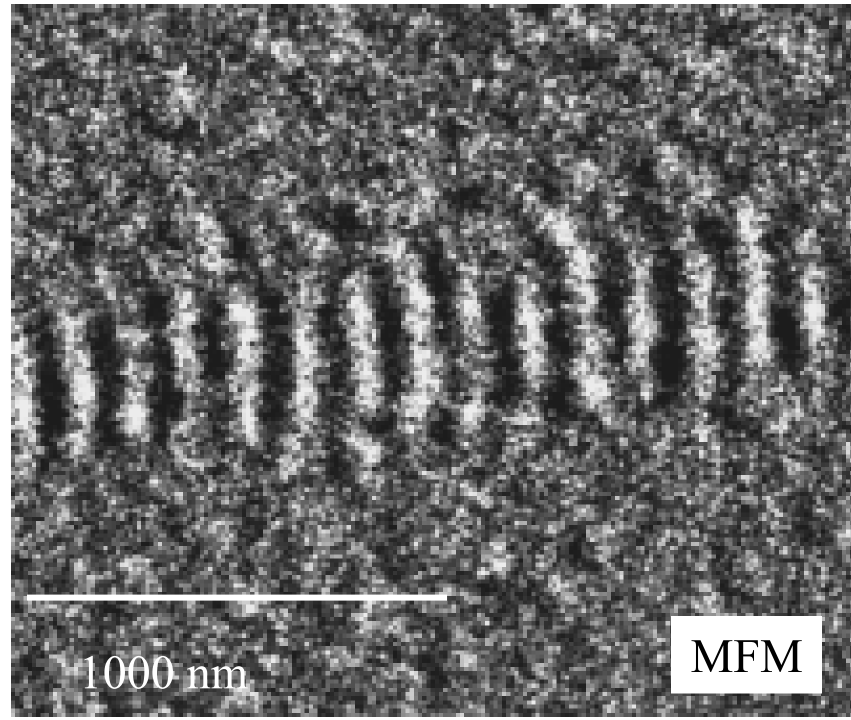
Media: TEM and MFM images

CoPtCrB alloy



100 nm

<D> = 8.5 nm

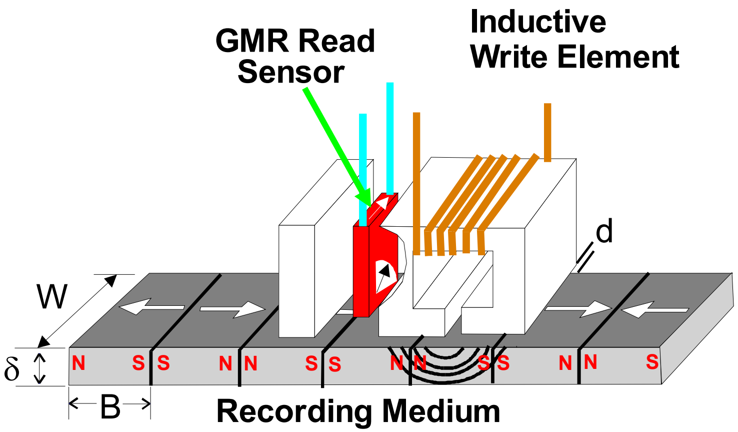


Eames, et al.
U. of Minn.

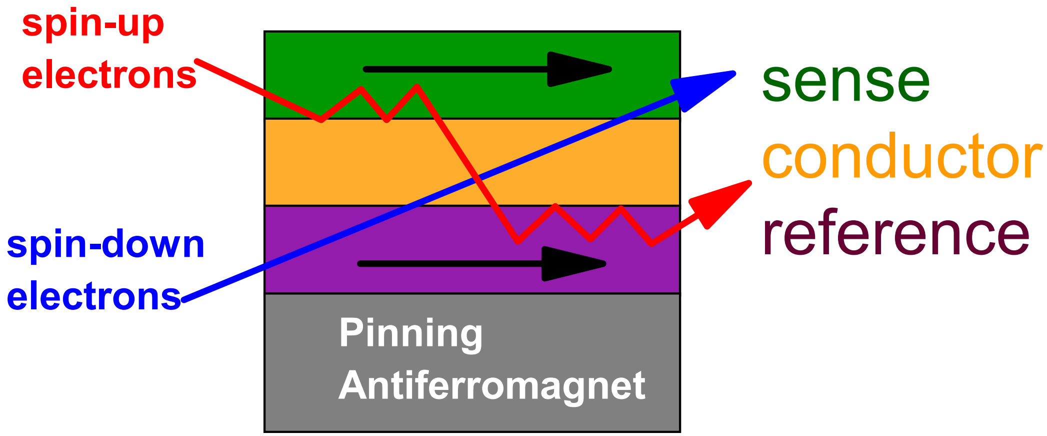
$\mathrm{SNR} \propto \sqrt{N}$ # grains/bit

More uniform the grains the better

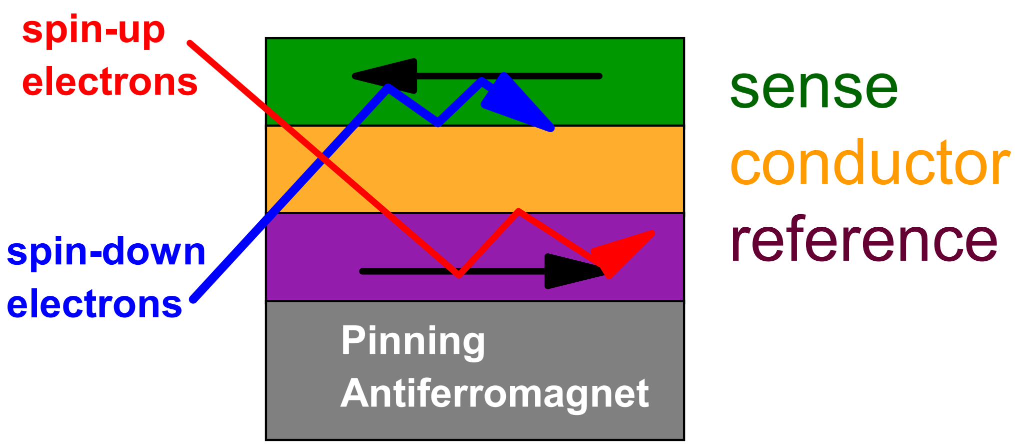
GMR sensor



GMR Read Sensor
Inductive Write Element
d
W
δ
B
N
S
Recording Medium

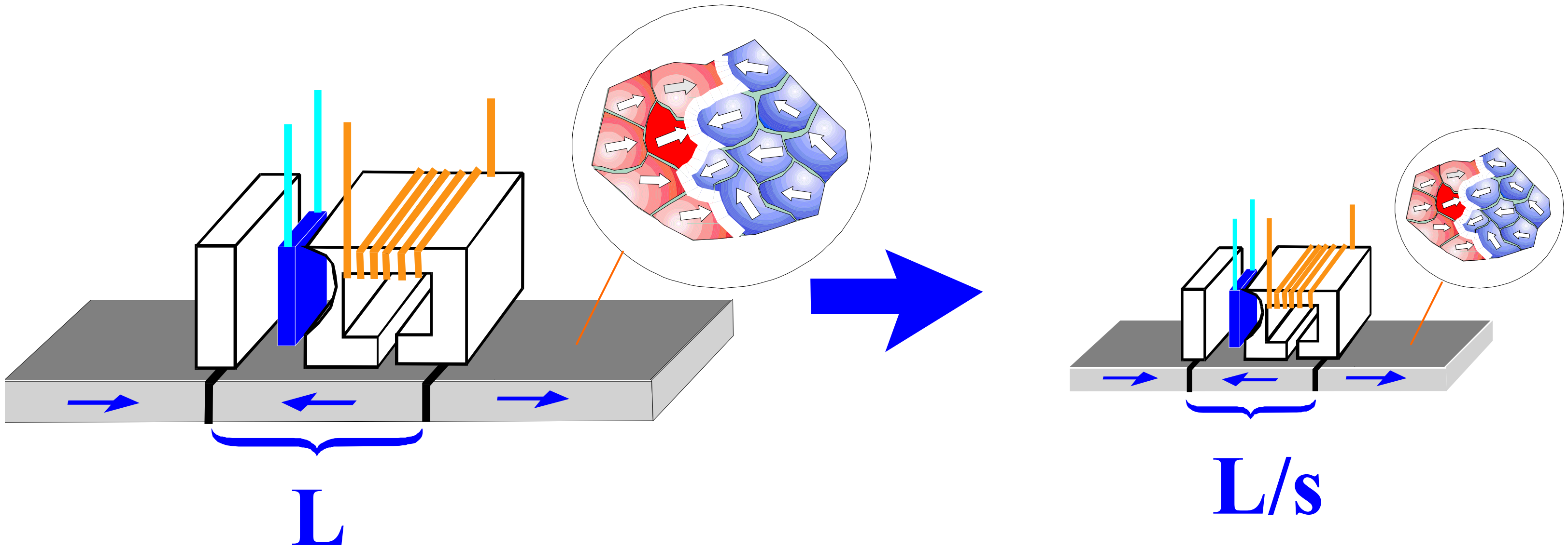


spin-up electrons
spin-down electrons
Pinning Antiferromagnet
sense
conductor
reference



spin-up electrons
spin-down electrons
Pinning Antiferromagnet
sense
conductor
reference

Scaling



→ Shrink everything by factor s (including currents and microstructure)

→Areal density of data increases s^2

But:

→Requires vastly improved processes

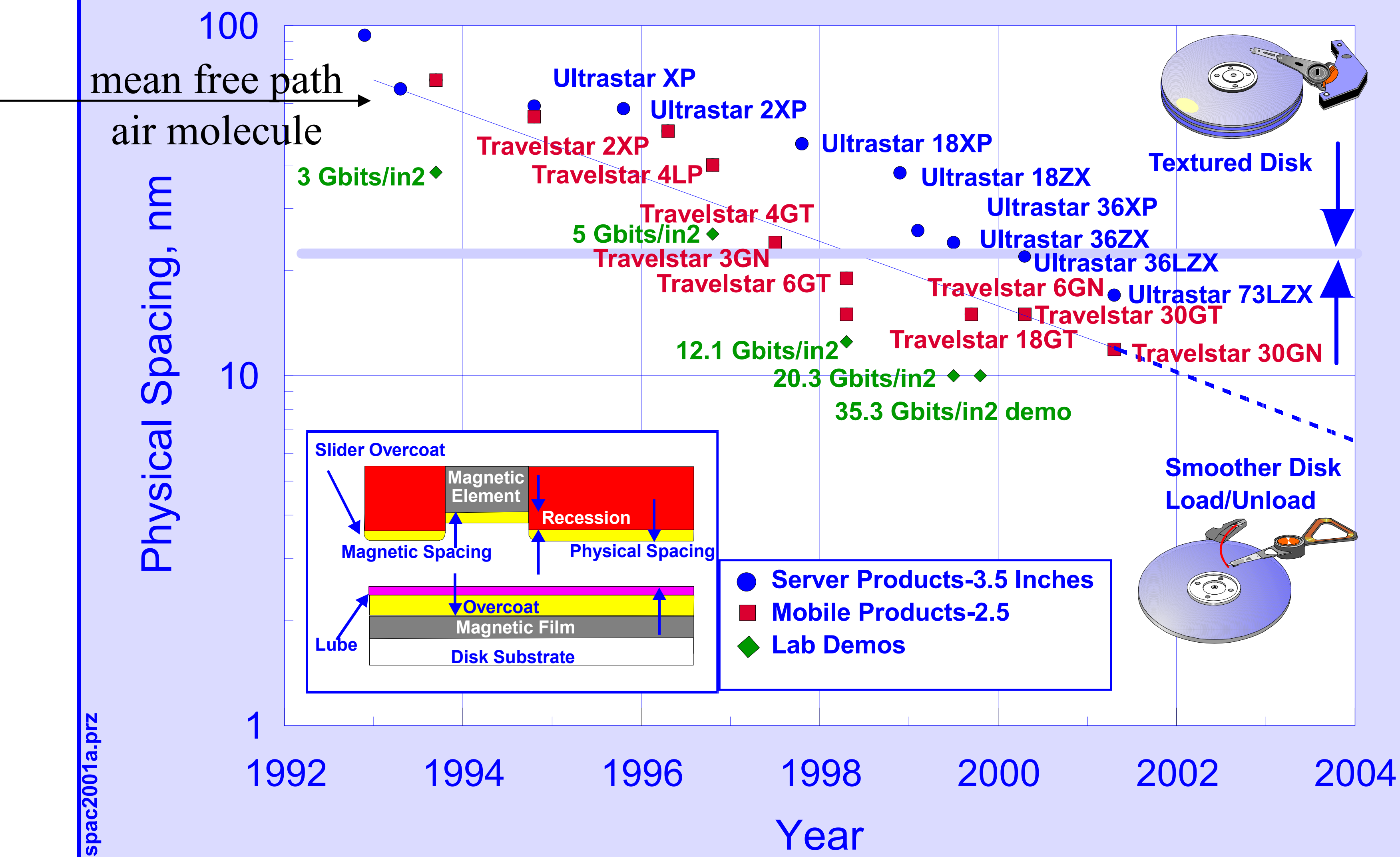
→ Signal to noise drops (→ improve media, head, electronics)

→ volumes scale by s^3 and surface/volume scales as 1/s

→ current densities increases by 1/s   (≈10^7 A/cm^2)

→ Physics no longer scales

Physical spacing and disk surface evolution

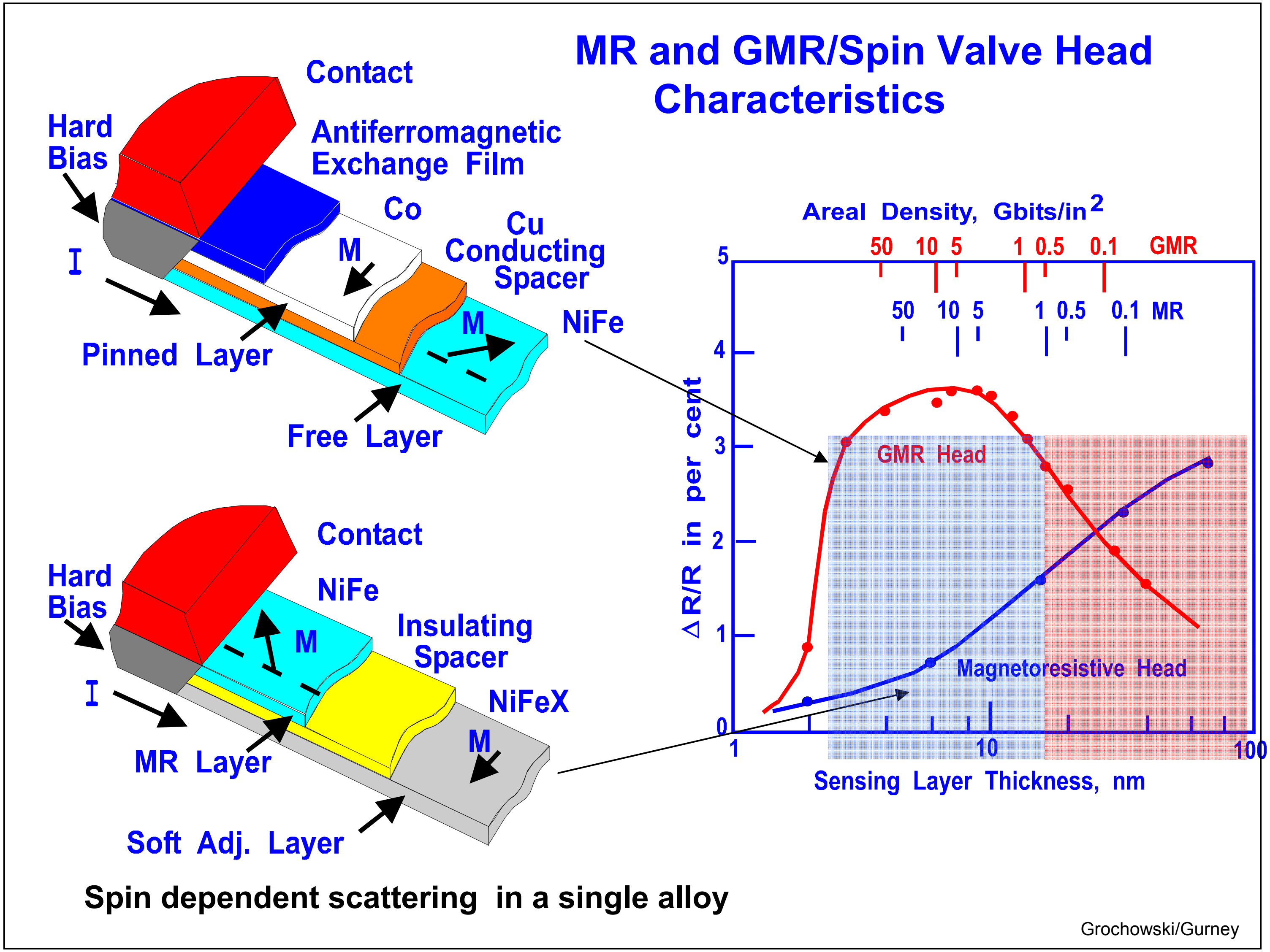


spac2001a.prz

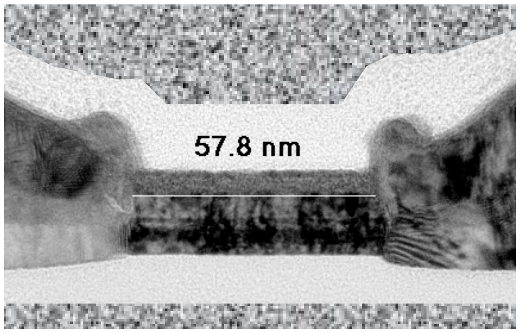
IBM

ED GROCHOWSKI at ALMADEN

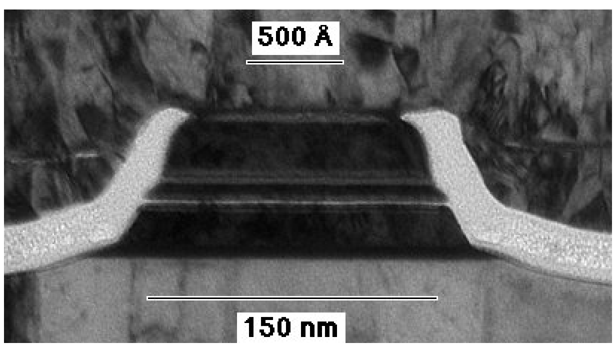
GMR sensors and scaling

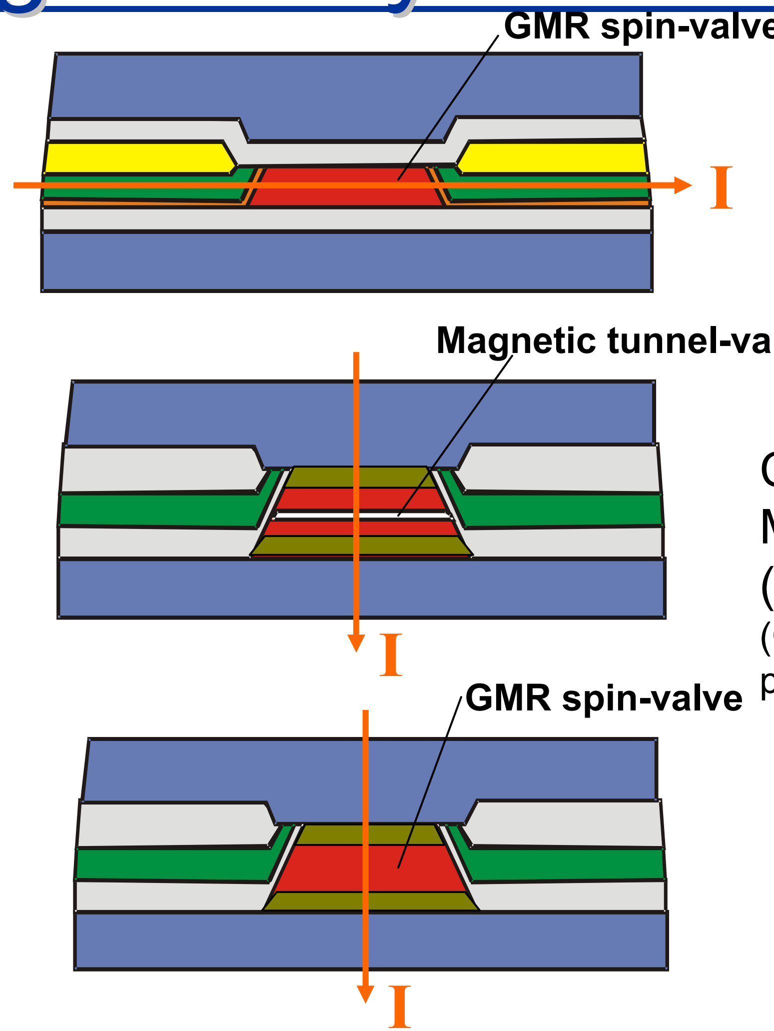


New sensor geometry



Tunnel-valve head



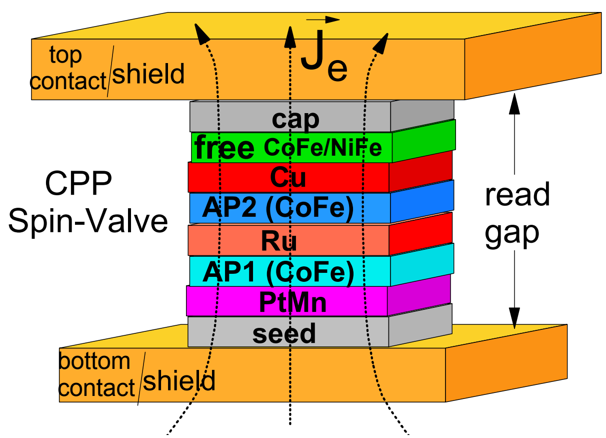


CIP-GMR
(Current-in-plane)

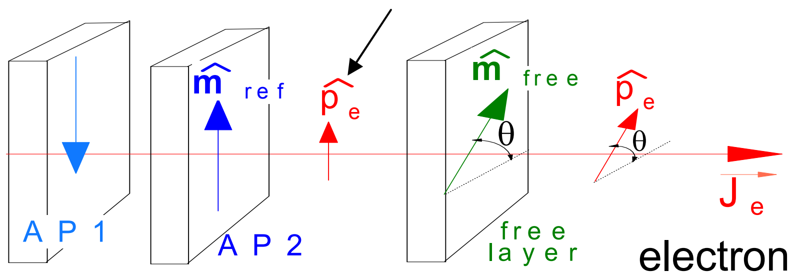
CPP-Tunnel Magnetoresistance (high R)
(Current-perpendicular-to-plane)

CPP-GMR (low R)
(Current-perpendicular-to-plane)

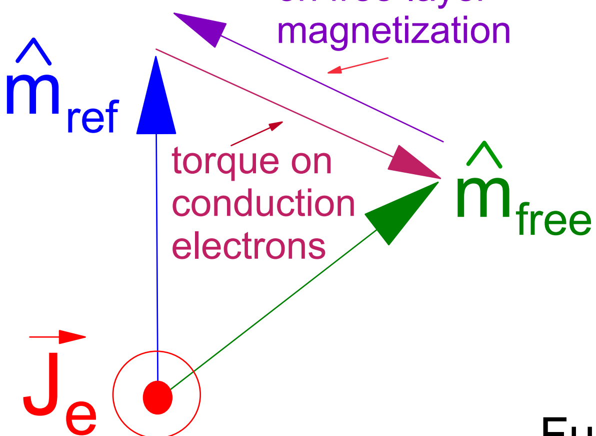
Spin torque effects



Polarized conduction electrons



electron current density



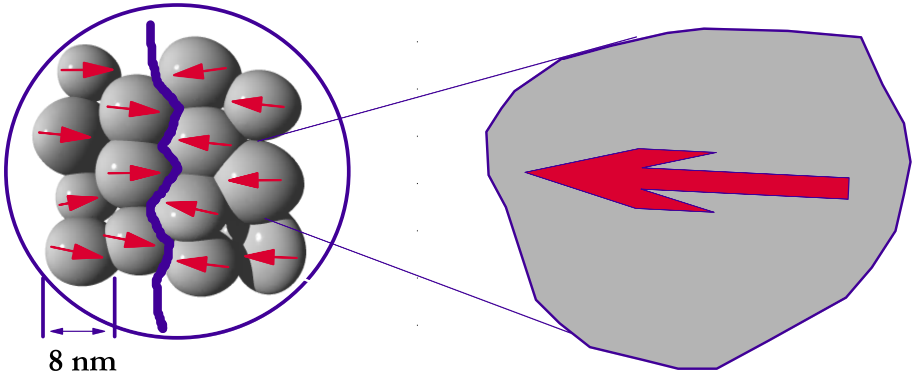
From simple angular momentum conservation (no reflections):

$$\Rightarrow \boxed{\frac{d\hat{m}_{\text{free}}}{dt} = \frac{\gamma\hbar}{2e}\frac{P\vec{J}_e}{M_s t_{\text{free}}}(\hat{m}_{\text{free}} \times \hat{m}_{\text{ref}} \times \hat{m}_{\text{free}})}$$

Depends on ***polarity*** of $\vec{J}_e$

Full ref: J. Slonczewski, JMMM **159**, L1 (1996)
Katine et al., PRL (2000)

Superparamagnetic limit



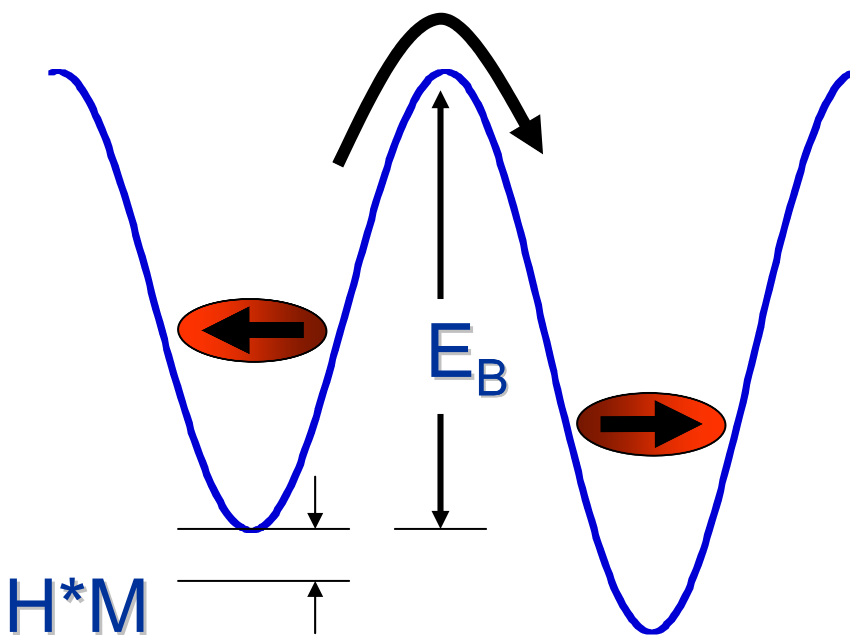
Magnetic energy $E = K_U V$

Increase E_B for stability:

$$\mathbf{E_B \sim K_U V(1\text{-}H/H_0)}$$

$$\tau^{-1} \sim f_0 \exp(-E_B/k_B T)$$

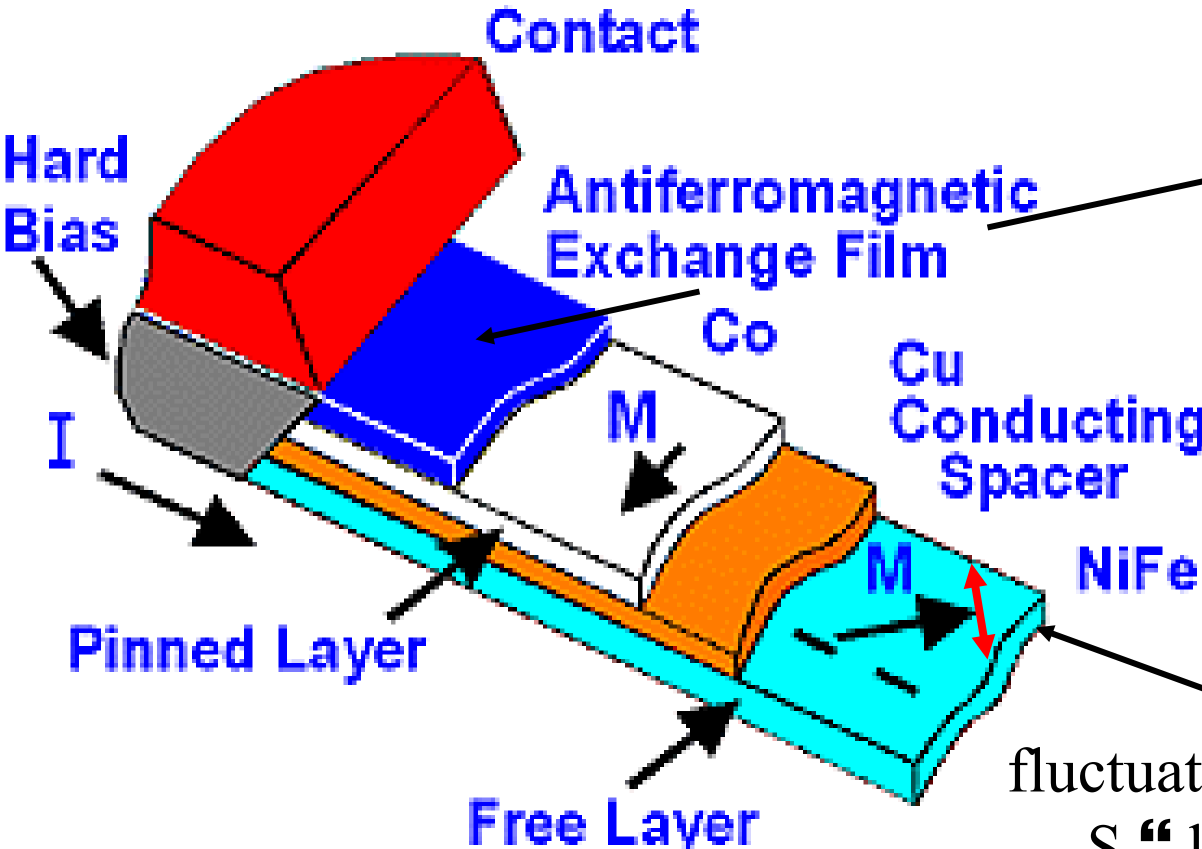
10^9/sec



But also need:

Coercive field $H_C \sim K_U/M_S < H_{Write\text{-}head}$

GMR sensor



Grains in AF layers

$K_U V_{AF} > 50 k_B T$

Carey *et al.*, JAP **89**, 6579 (2001).

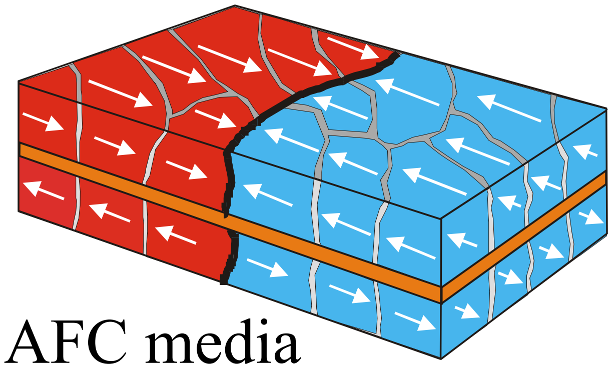
Thermal fluctuations

fluctuation-dissipation theorem

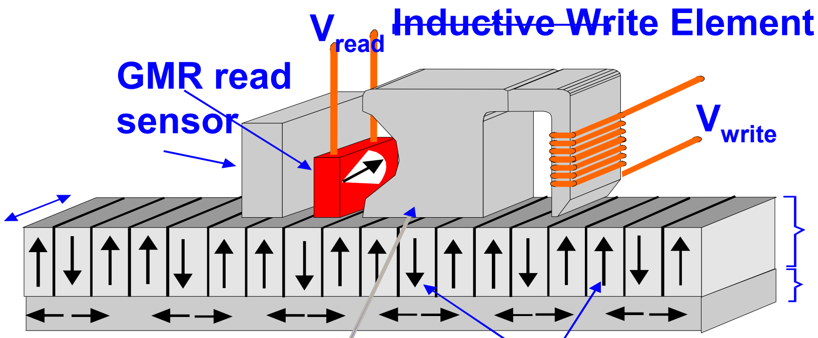
$S \propto k_B T / M V_{free}$

Smith and Arnett, APL **78**, 1448 (2001).

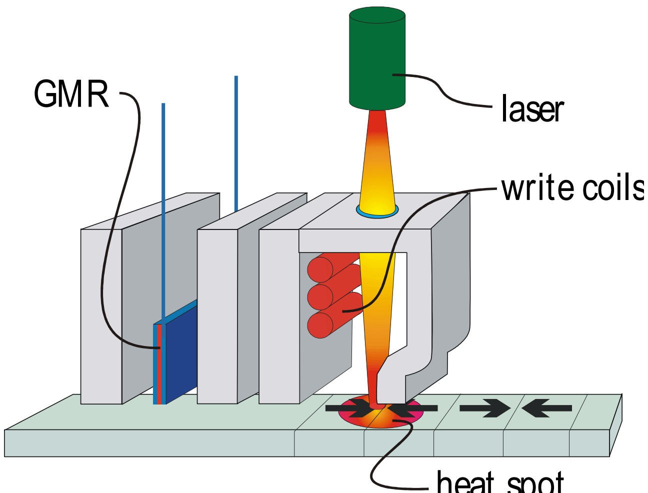
Advanced media and systems



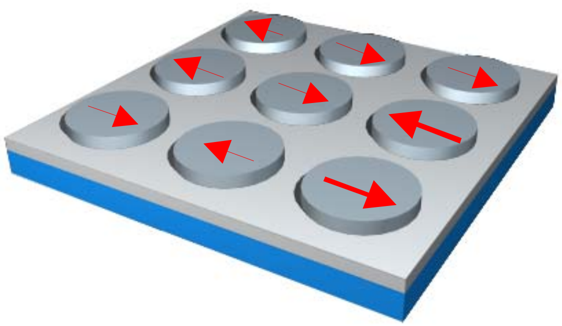
AFC media



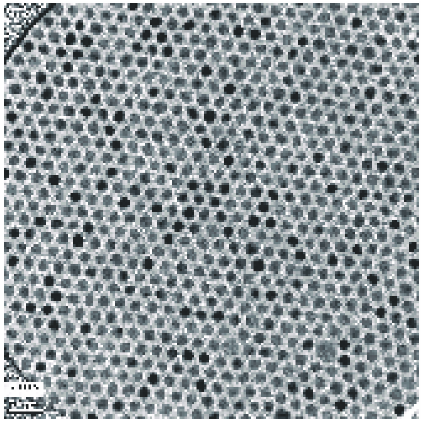
Perpendicular recording



Thermal assisted recording



patterned media



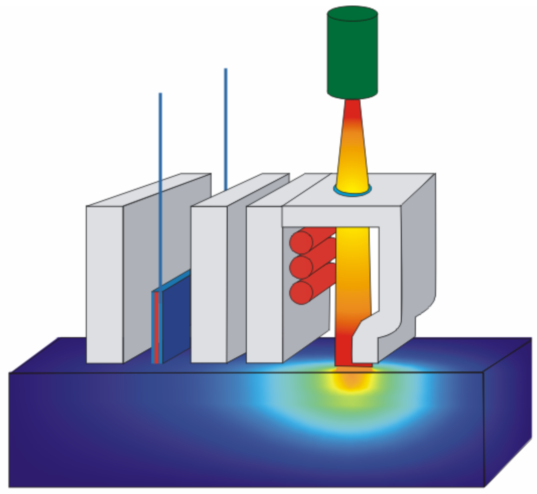
S. Sun, IBM

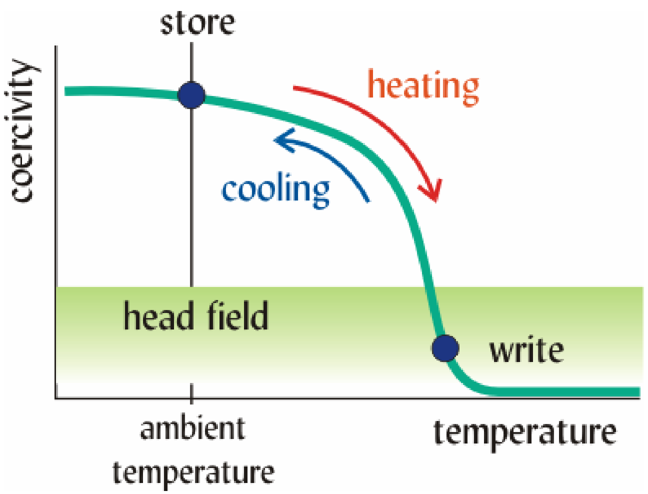
self-organized media

Moser et al., J. Phys. D: Appl. Phys. **35**, R157 (2002).

Terris and Thomson, J. Phys. D: Appl. Phys. **38**, 199 (2005).

Thermally Assisted Recording

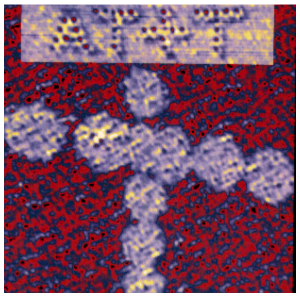




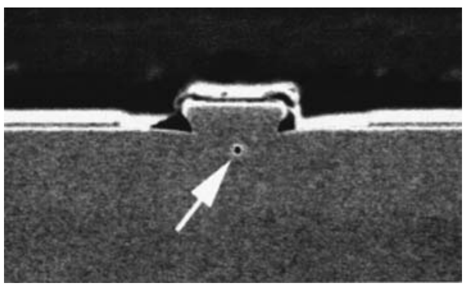
What are the key media and head requirements ?

- optical/thermal efficiency
- sub-100 nm heat spot overlapping with magnetic field
- 200 C heating/cooling in 1 ns
- high-K_U, moderate T_{write}, small grain size & distribution

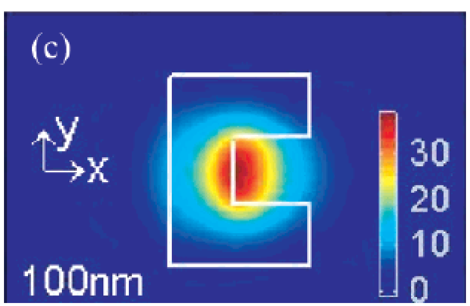
Thermally Assisted Recording



E. Betzig, et al., Appl. Phys. Lett., **61**, 142 (1992)



Partovi et al., *Appl Phys. Lett*. **75**, 1515 (1999)



X. Shi, L. Hesselink, JJAP 41-3B (2002) p1632

Far field, the light intensity normalized to the incident intensity and hole diameter is

P_{far}/Area ➩ (d/ κ)^4

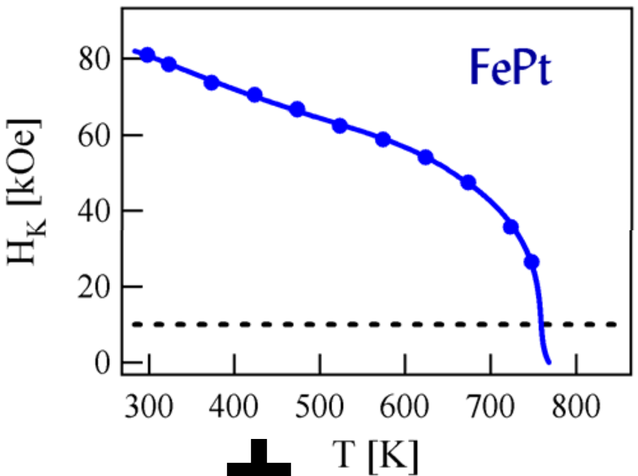
close to the hole, the normalized intensity is

P_{close}/Area ➩ (d/ κ)^2

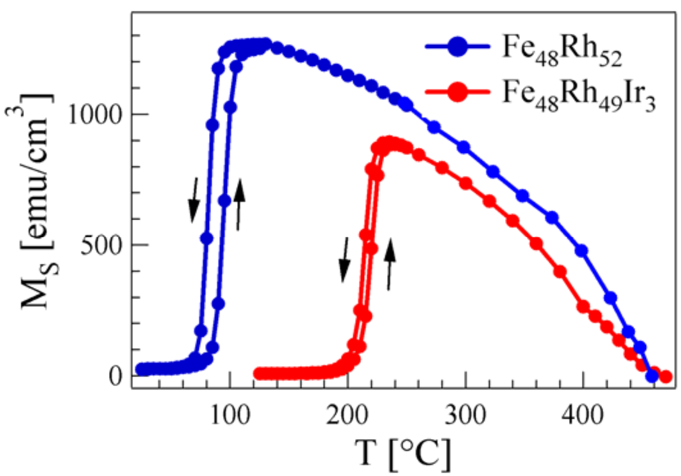
H. A. Bethe, *Phys. Rev*. **66**, 163 (1944)

resonant structures seem to provide required transmission

Two layer recording media

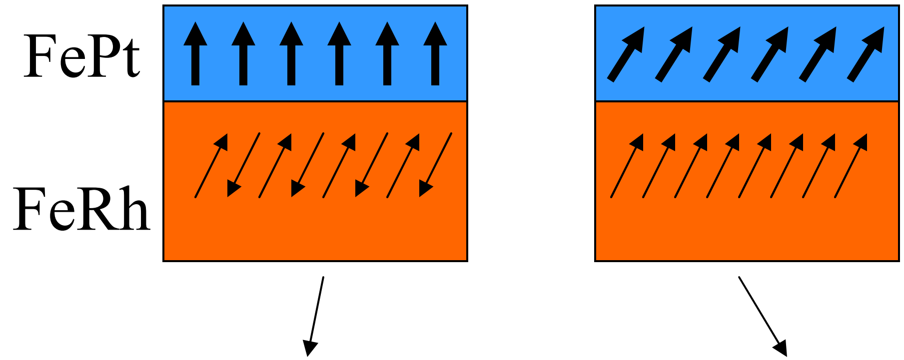


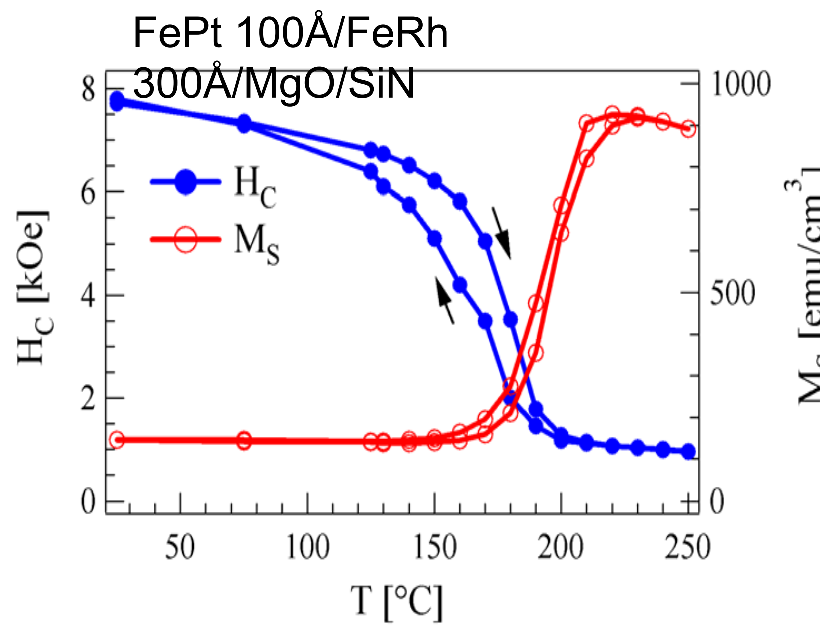
+



R. M. Moon *et al*., J. Appl. Phys. 36 (1965) p978

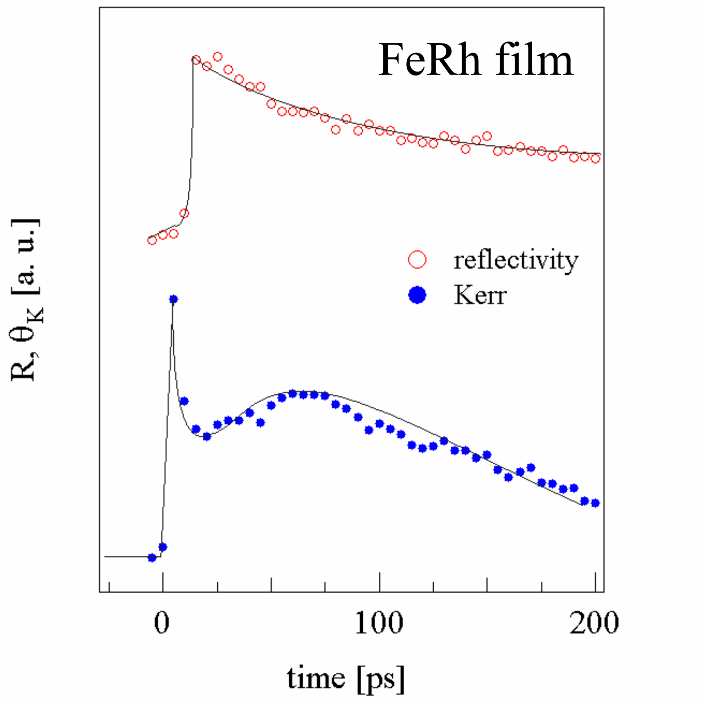
$\Rightarrow$

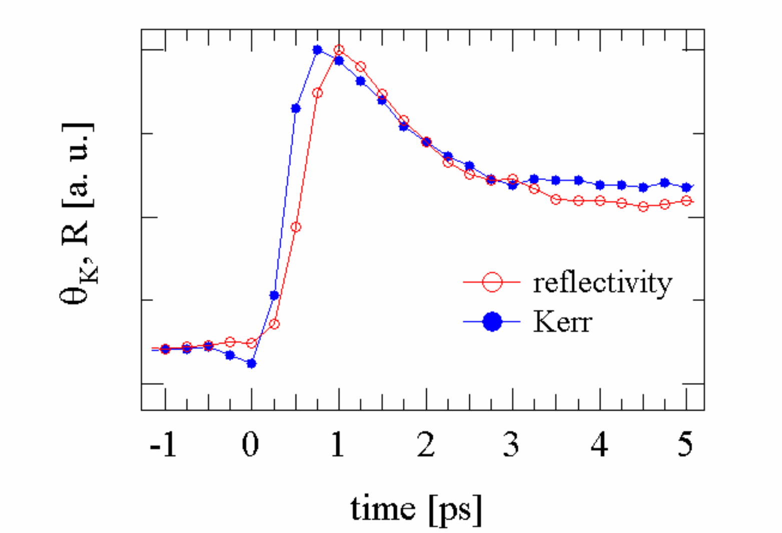


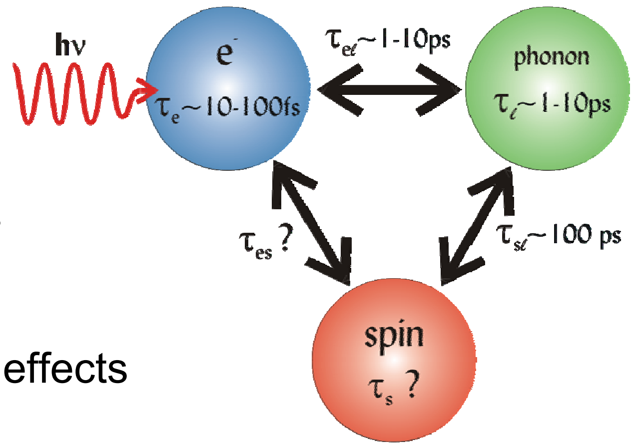


Thiele *et al.*, Appl. Phys. Lett. **82**, 2859 (2003).

Two layer recording media





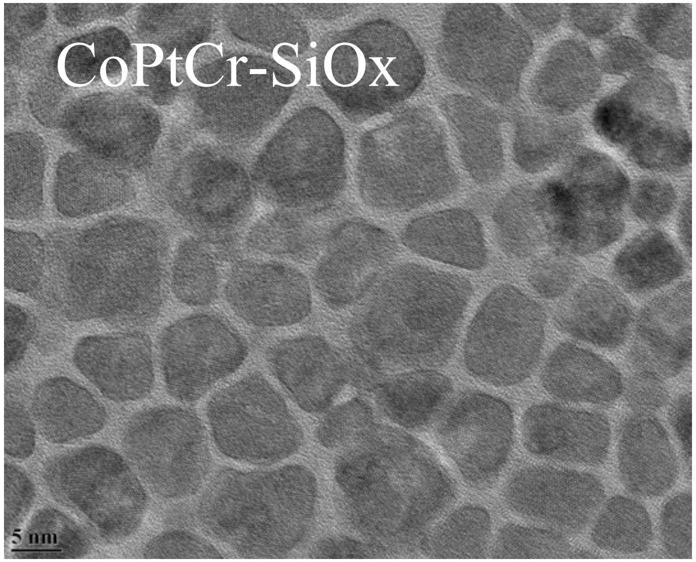


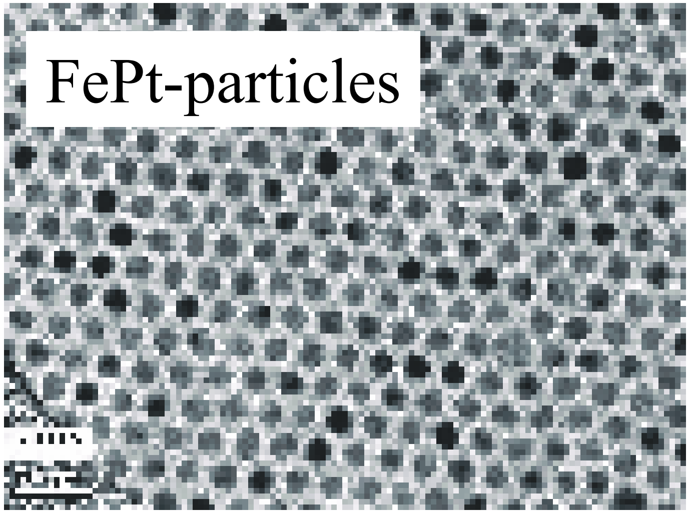
- Kerr response on 10ps time scale qualitatively resembles expected behavior,
- rise time ~ 500 fs: AF-FM transition can be fast
- too fast for lattice – AF-FM transition driven by electronic effects
- interesting physics

J.-U. Thiele. M. Buess, C. H. Back, Appl. Phys. Lett. **85** (2004) p2857

Nano 'issues'

- control of nano structural order
  - chemical segregation
  - lithography
  - self-assembly
- thermal energy
  - spin wave modes of small structures
  - collective modes
- high current densities
  - dipole fields, spin torques, heating
- sub-ns reversal
- particle-to-particle variations
- particle-to-particle interactions

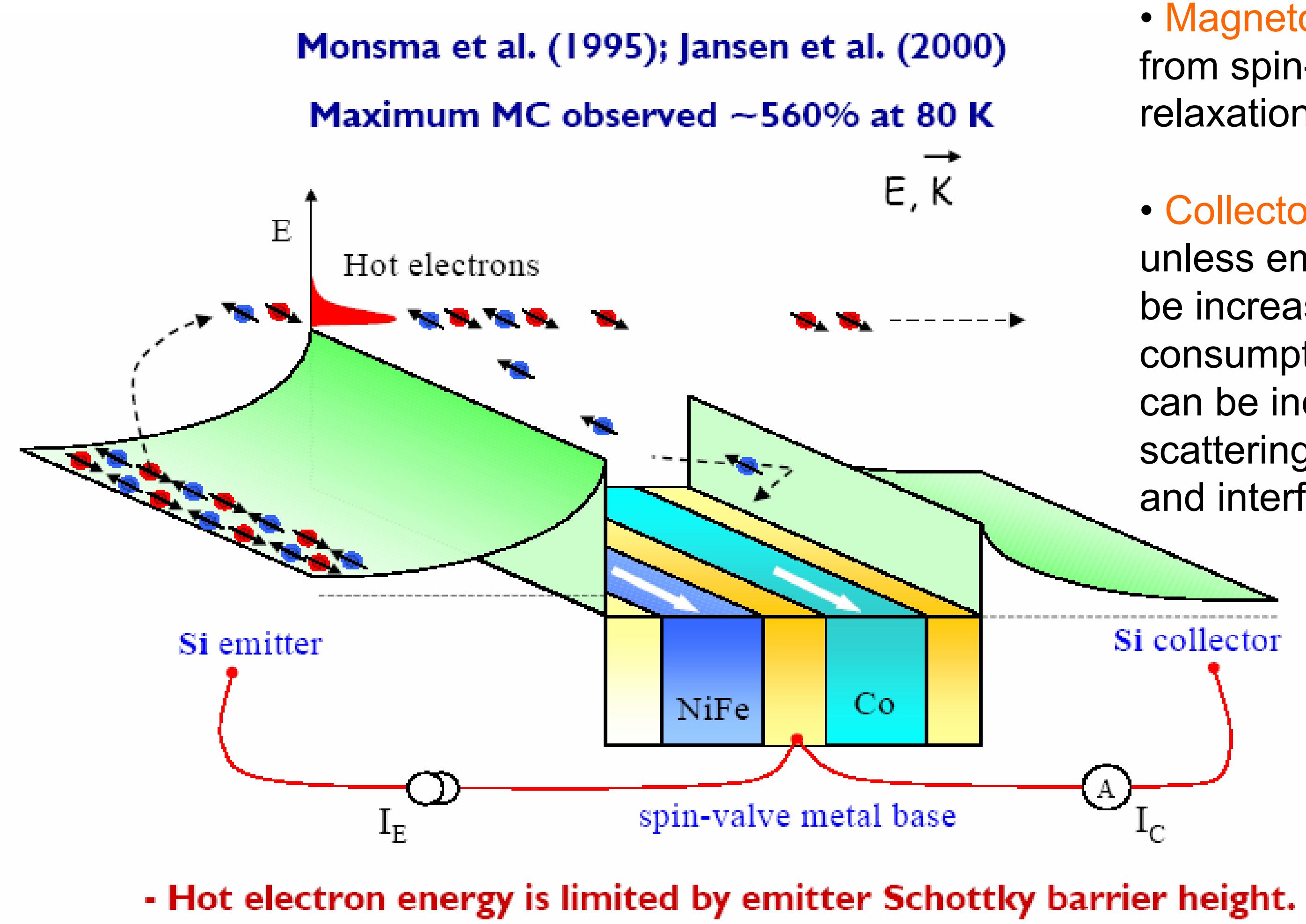




Nano solutions

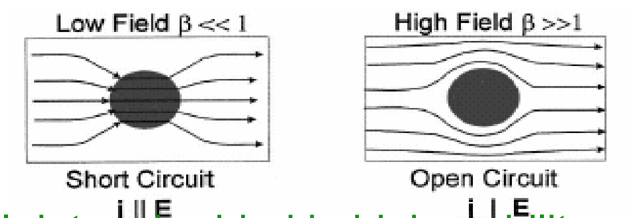
- New materials and architectures
  - Combine disparate materials at the nm scale
    - e.g. magnet/non-magnetic/magnetic (GMR and RKKY interlayer coupling)
    - FM/AF layers: exchange bias
  - Metal/semiconductor
  - Move to 3D hetero-structures
  - Competing interactions

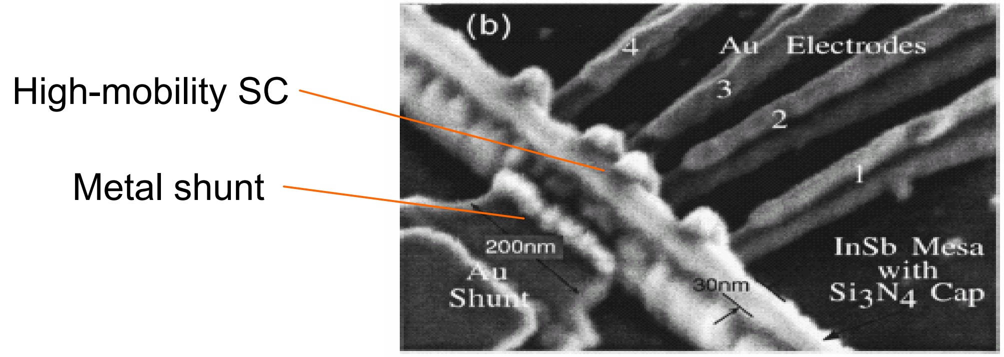
Spin-valve Transistor



- Magnetoconductance (>400%) from spin-dependant hot-electron relaxation in spin-valve base.
- Collector current small (µA) unless emission current Ie can be increased (breakdown, power consumption) or transfer ratio can be increased (thinner, less scattering non-magnetic layers and interfaces)

Extraordinary Magnetoresistance (EMR)



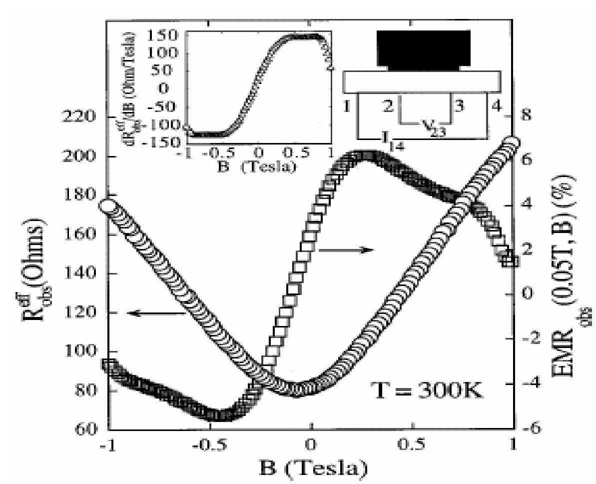


Solin, APL 80, 4012 (2001)

Metal dot embedded in high mobility
low carrier density semiconductor (i.e. InSb).

At low field E is _|_ to metal/SC boundary and
j follows E → low R.

At high fields because of the Lorentz force the
angle between j and E can approach 90 degrees
with little current flowing through metal → high R.



Nano solutions

- Characterization at the relevant time and length scales.
  - Both magnetic and structural sensitivity
  - atomic depth resolution
  - <10 nm lateral resolution
  - <ns temporal resolution
  - buried interfaces
- Neutron and synchrotron facilities are key
  - Resonant x-ray techniques
  - Elemental and magnetic sensitivity via core level resonances, 1-2 nm wavelengths, scattering and imaging down to ♓30 ps time resolution.